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ARTIFICIAL INTELLIGENCE-ASSISTED PREDICTION OF HIGH-RISK PREGNANCY OUTCOMES IN RURAL AND URBAN HEALTHCARE SETTINGS OF PAKISTAN

Dr Naila Izhar Qazi[*1], Zarmina Bibi[2], Tanzeela Ahmad[3]

[*1]*Senior Registrar, Ob/gyn, BUHSCK*
[2]*Senior Rejister Gynea and Obs Teaching Hospital Loarali*
[3]*Consultant, Department of Obstetrics and Gynaecology, Iqra Medical Complex Hospital Johar town, Lahore*

[*1]izharqazi@hotmail.com, [2]zarminakhan1755@gmail.com, [3]drtanzeelaahmad@yahoo.com

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Corresponding Author: *
Dr Naila Izhar Qazi

Abstract

This study developed and evaluated an Artificial Intelligence (AI)-assisted predictive framework for identifying high-risk pregnancy outcomes in rural and urban healthcare settings of Pakistan. Despite improvements in maternal healthcare services, Pakistan continues to experience high rates of maternal and neonatal complications due to delayed risk identification, limited healthcare resources, and disparities between rural and urban healthcare infrastructure. To address this issue, a quantitative predictive analytics design was employed using retrospective maternal healthcare data obtained from multiple healthcare institutions. The dataset included demographic, clinical, socioeconomic, and healthcare accessibility variables, which were analyzed using multiple machine learning algorithms including Random Forest, XGBoost, Support Vector Machine (SVM), Artificial Neural Network (ANN), and Long Short-Term Memory (LSTM) models. The results indicated that AI-based models achieved high predictive accuracy in identifying high-risk pregnancies, with LSTM and XGBoost outperforming other algorithms. Clinical indicators such as blood pressure, blood glucose levels, BMI, and previous pregnancy complications emerged as the most significant predictors of adverse pregnancy outcomes. Comparative analysis further revealed slightly higher predictive performance in urban healthcare settings compared to rural settings; however, overall model performance remained strong across both contexts. The findings confirmed that AI-assisted predictive systems significantly enhance early risk detection and support clinical decision-making in maternal healthcare.

The study concludes that integrating AI-driven clinical decision support systems into maternal healthcare services can improve early identification of high-risk pregnancies, optimize resource allocation, and contribute to improved maternal and neonatal outcomes in Pakistan. The findings provide valuable implications for healthcare practitioners, policymakers, and researchers aiming to strengthen digital health transformation in maternal care.

INTRODUCTION

Maternal and neonatal health remains a critical public health priority worldwide, particularly in low- and middle-income countries where preventable pregnancy-related complications

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continue to contribute significantly to morbidity and mortality. Despite substantial progress in maternal healthcare over the past two decades, adverse pregnancy outcomes such as preeclampsia, gestational diabetes mellitus, preterm birth, fetal growth restriction, stillbirth, and maternal mortality remain major challenges. Early identification of high-risk pregnancies is essential for timely clinical intervention, effective resource allocation, and improved maternal and neonatal outcomes. Traditional risk assessment approaches primarily rely on clinicians' expertise, routine antenatal examinations, and standardized screening protocols. However, these methods often face limitations in accurately identifying complex interactions among multiple risk factors, particularly in resource-constrained healthcare environments. Consequently, the integration of Artificial Intelligence (AI) into maternal healthcare has emerged as a promising strategy for enhancing predictive accuracy and supporting clinical decision-making processes (Islam et al., 2022; Lin et al., 2024).

Artificial Intelligence refers to computational systems capable of simulating human cognitive functions, including learning, reasoning, prediction, and decision-making. Within healthcare, AI technologies—particularly machine learning (ML), deep learning (DL), and predictive analytics—have demonstrated remarkable capabilities in identifying hidden patterns from large-scale clinical datasets. These technologies can process complex demographic, obstetric, clinical, behavioral, and socioeconomic variables simultaneously, enabling healthcare providers to predict adverse outcomes before the onset of severe complications. Recent studies have shown that machine learning algorithms such as Random Forest, XGBoost, Support Vector Machines (SVM), Artificial Neural Networks (ANN), and Gradient Boosting models outperform conventional statistical approaches in predicting pregnancy-related risks and maternal complications (Ranjbar et al., 2024; Hassan, 2025).

The increasing availability of electronic health records, digital maternal registries, wearable monitoring devices, and mobile health technologies has further accelerated the adoption of AI-assisted predictive systems in obstetric care. AI-based clinical decision support systems can assist healthcare professionals in identifying women who are at elevated risk for adverse pregnancy outcomes, thereby facilitating earlier interventions, personalized treatment strategies, and more efficient utilization of healthcare resources. Systematic reviews indicate that AI-enhanced maternal healthcare systems can significantly improve the prediction of preeclampsia, gestational diabetes, cesarean delivery risks, maternal morbidity, neonatal complications, and preterm birth by leveraging multidimensional healthcare data (Lin et al., 2024; Vasudevan et al., 2025).

The application of AI in maternal healthcare is particularly relevant in developing countries where healthcare resources are limited and healthcare inequalities persist. Pakistan continues to experience substantial maternal and neonatal health challenges despite ongoing healthcare reforms and improvements in healthcare infrastructure. Factors such as inadequate antenatal care, delayed diagnosis, shortage of specialized obstetric services, poor healthcare accessibility, socioeconomic disparities, and geographical barriers contribute to adverse maternal and neonatal outcomes. These challenges are especially pronounced in rural regions, where healthcare facilities often lack advanced diagnostic equipment, specialized healthcare professionals, and comprehensive maternal monitoring systems. In contrast, urban healthcare centers generally possess greater technological resources, specialized personnel, and improved access to healthcare services. This disparity creates significant variations in pregnancy management and health outcomes between rural and urban populations.

The rural–urban healthcare divide in Pakistan presents a unique context for investigating AI-assisted predictive models. Rural populations frequently encounter barriers related to transportation, healthcare accessibility, financial constraints, and limited health literacy, which may delay the identification and management of high-risk pregnancies. Conversely, urban healthcare

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institutions generate substantial volumes of digital health data that can facilitate the development of sophisticated predictive algorithms. Consequently, examining the performance and applicability of AI-based risk prediction systems across both rural and urban healthcare settings is essential for understanding their effectiveness, scalability, and equity implications within Pakistan's healthcare system.

Globally, numerous studies have explored the use of machine learning techniques for predicting pregnancy complications. A systematic review by Islam et al. (2022) identified substantial growth in the application of machine learning algorithms for maternal risk assessment, highlighting their potential to improve predictive performance compared to traditional approaches. Similarly, Ranjbar et al. (2024) reported that machine learning models demonstrate considerable effectiveness in predicting preeclampsia, one of the leading causes of maternal morbidity and mortality worldwide. Furthermore, recent investigations have emphasized the importance of explainable artificial intelligence (XAI) in maternal healthcare, enabling clinicians to understand model predictions and increasing trust in AI-supported clinical decision-making processes (Özcan & Peker, 2024; Hassan, 2025).

Despite these advancements, the majority of existing studies have been conducted in high-income countries with advanced healthcare infrastructure and well-established electronic health record systems. Evidence regarding the application of AI-assisted pregnancy risk prediction models in low- and middle-income countries remains limited. More importantly, few studies have examined how AI-driven predictive systems perform across diverse healthcare environments characterized by significant disparities in healthcare access, socioeconomic conditions, and technological readiness. In Pakistan, research investigating AI applications in maternal healthcare is still in its infancy, and comparative analyses between rural and urban healthcare settings remain largely unexplored. Existing studies have primarily focused on general healthcare applications rather than developing context-specific predictive frameworks that incorporate demographic, clinical, socioeconomic, and environmental determinants relevant to Pakistani populations.

Given the growing burden of maternal health complications and the increasing availability of healthcare data, there is an urgent need to develop AI-assisted predictive models tailored to Pakistan's healthcare context. Such models have the potential to support healthcare providers in early identification of high-risk pregnancies, facilitate timely referrals, optimize healthcare resource allocation, and reduce preventable maternal and neonatal complications. Therefore, this study aims to investigate the effectiveness of Artificial Intelligence-assisted prediction systems for identifying high-risk pregnancy outcomes in rural and urban healthcare settings of Pakistan. By integrating clinical, demographic, socioeconomic, and healthcare accessibility factors, the study seeks to contribute to the advancement of data-driven maternal healthcare and provide evidence-based recommendations for healthcare practitioners and policymakers.

Problem Statement

Maternal and neonatal health continues to represent a significant public health challenge in Pakistan despite ongoing efforts to improve healthcare infrastructure and maternal healthcare services. Pregnancy-related complications such as preeclampsia, gestational diabetes mellitus, preterm birth, low birth weight, fetal distress, and maternal mortality remain prevalent, particularly among vulnerable populations residing in underserved regions. A substantial proportion of these adverse outcomes can be prevented through timely identification of risk factors and early clinical intervention. However, current maternal healthcare systems in Pakistan predominantly rely on conventional risk assessment methods that depend heavily on clinical judgment, periodic antenatal examinations, and standardized screening procedures. These approaches often fail to capture the complex interactions among demographic, clinical, socioeconomic, and environmental factors that contribute to high-risk pregnancies.

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The challenge is further intensified by pronounced disparities between rural and urban healthcare systems. Urban healthcare facilities generally benefit from better infrastructure, specialist availability, advanced diagnostic technologies, and electronic health information systems. In contrast, rural healthcare centers frequently encounter shortages of trained healthcare professionals, inadequate diagnostic resources, limited maternal monitoring capabilities, and restricted access to specialist care. Consequently, many high-risk pregnancies remain unidentified until complications become severe, increasing the likelihood of adverse maternal and neonatal outcomes.

Recent advances in Artificial Intelligence and machine learning have demonstrated substantial potential in predicting pregnancy complications and supporting clinical decision-making. AI-assisted predictive models can analyze large volumes of healthcare data, identify hidden risk patterns, and generate accurate predictions that facilitate proactive intervention strategies. Nevertheless, most existing studies have been conducted in developed healthcare environments characterized by robust digital infrastructure and comprehensive electronic health records. Limited evidence exists regarding the applicability, effectiveness, and scalability of AI-assisted pregnancy risk prediction systems within resource-constrained healthcare settings such as Pakistan. Furthermore, there is a lack of empirical research examining whether AI-based predictive models perform differently across rural and urban healthcare contexts where patient characteristics, healthcare accessibility, and resource availability vary considerably.

Another critical gap concerns the integration of multidimensional predictors within maternal healthcare models. Existing studies often focus primarily on clinical variables while overlooking socioeconomic determinants, healthcare accessibility indicators, environmental conditions, and demographic characteristics that significantly influence pregnancy outcomes in developing countries. Consequently, current evidence provides limited guidance for healthcare practitioners and policymakers seeking to implement context-specific AI solutions capable of addressing maternal health disparities across Pakistan.

Therefore, a significant research gap exists regarding the development and evaluation of AI-assisted predictive frameworks that incorporate comprehensive risk factors and assess their effectiveness in both rural and urban healthcare settings. Addressing this gap is essential for improving early detection of high-risk pregnancies, enhancing clinical decision-making, reducing maternal and neonatal complications, and supporting evidence-based healthcare policies aimed at strengthening maternal health outcomes throughout Pakistan.

Research Questions

1. What demographic, clinical, socioeconomic, and healthcare accessibility factors significantly influence high-risk pregnancy outcomes in Pakistan?
2. How effectively can Artificial Intelligence models predict high-risk pregnancy outcomes among pregnant women in Pakistan?
3. Which machine learning algorithm demonstrates the highest predictive accuracy for identifying high-risk pregnancies?
4. Does the predictive performance of AI-assisted models differ between rural and urban healthcare settings?
5. How can AI-assisted prediction systems contribute to improved maternal and neonatal healthcare outcomes in Pakistan?

Research Objectives

1. To identify the demographic, clinical, socioeconomic, and healthcare accessibility factors associated with high-risk pregnancy outcomes in Pakistan.
2. To develop an Artificial Intelligence-assisted predictive model for the early identification of high-risk pregnancies.
3. To evaluate the predictive performance of different machine learning algorithms in forecasting adverse pregnancy outcomes.
4. To compare the effectiveness of AI-assisted prediction models across rural and urban healthcare settings.

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5. To examine the potential contribution of AI-assisted prediction systems toward improving maternal and neonatal healthcare outcomes in Pakistan.

Significance of the Study

Theoretical Significance

This study contributes to the growing body of knowledge on Artificial Intelligence applications in maternal healthcare by extending predictive analytics research to the context of developing countries. It integrates concepts from healthcare informatics, clinical decision support systems, and predictive modeling to develop a comprehensive framework for identifying high-risk pregnancies. The study also enriches existing literature by incorporating demographic, clinical, socioeconomic, and healthcare accessibility variables within a unified predictive model, thereby offering a broader understanding of determinants influencing pregnancy outcomes.

Practical Significance

The study provides valuable insights for healthcare professionals, obstetricians, gynecologists, and maternal health practitioners by demonstrating how AI-assisted systems can support early risk identification and clinical decision-making. The proposed predictive framework may enable healthcare providers to prioritize high-risk cases, improve referral mechanisms, optimize resource utilization, and implement timely interventions that reduce maternal and neonatal complications. Furthermore, the findings may facilitate the development of intelligent maternal healthcare tools suitable for both technologically advanced urban hospitals and resource-constrained rural healthcare centers.

Policy Significance

From a policy perspective, the study offers evidence-based recommendations for integrating Artificial Intelligence technologies into Pakistan's maternal healthcare system. The findings may assist policymakers in designing data-driven maternal health strategies, strengthening digital health initiatives, and reducing healthcare inequalities between rural and urban populations. The study also supports national and international efforts aimed at achieving sustainable development goals related to maternal and child health by promoting equitable access to advanced healthcare technologies and improving maternal health outcomes across Pakistan.

Literature Review

Artificial Intelligence in Maternal Healthcare

Artificial Intelligence (AI) has emerged as a transformative technology in healthcare, facilitating improved diagnosis, prediction, and clinical decision-making. AI encompasses computational techniques that enable machines to learn from data, identify patterns, and make predictions with minimal human intervention. In maternal healthcare, AI applications have gained increasing attention due to their potential to enhance risk assessment, early detection of complications, and personalized healthcare delivery. The integration of machine learning algorithms with electronic health records, maternal health databases, and digital monitoring systems has significantly improved predictive capabilities in obstetric care (Islam et al., 2022).

Traditional pregnancy risk assessment methods largely depend on clinical expertise, routine screening procedures, and standard statistical approaches. However, these methods often fail to capture the complex interactions among multiple maternal, clinical, socioeconomic, and environmental risk factors. AI-based predictive systems address these limitations by analyzing large volumes of multidimensional data and identifying hidden relationships that may not be apparent through conventional techniques. Consequently, AI-assisted prediction models have demonstrated superior predictive performance in identifying adverse pregnancy outcomes compared to traditional statistical models (Lin et al., 2024).

Recent advancements in machine learning and deep learning have enabled healthcare providers to predict pregnancy-related complications with greater accuracy and timeliness. Studies indicate that AI-based systems can effectively support healthcare professionals in identifying high-risk pregnancies, thereby facilitating timely intervention and reducing maternal and neonatal

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morbidity and mortality. The growing recognition of AI as a clinical decision-support tool highlights its potential role in strengthening maternal healthcare systems globally.

High-Risk Pregnancy Outcomes

A high-risk pregnancy is characterized by conditions that increase the likelihood of adverse maternal or fetal outcomes. These conditions may arise from pre-existing medical disorders, pregnancy-related complications, demographic characteristics, behavioral factors, or environmental influences. Common high-risk pregnancy outcomes include preeclampsia, gestational diabetes mellitus, preterm birth, fetal growth restriction, low birth weight, stillbirth, maternal morbidity, and maternal mortality (World Health Organization [WHO], 2024).

Globally, maternal mortality remains a major public health concern despite substantial improvements in healthcare services. Developing countries continue to account for the majority of maternal deaths due to inadequate healthcare infrastructure, limited access to specialized care, and socioeconomic inequalities. Pakistan faces similar challenges, particularly in rural regions where healthcare facilities often lack specialized obstetric services and advanced diagnostic technologies. Consequently, early identification and management of high-risk pregnancies have become critical priorities for improving maternal and neonatal health outcomes.

Researchers emphasize that timely risk prediction enables healthcare providers to implement preventive measures, monitor vulnerable pregnancies more effectively, and optimize healthcare resource allocation. Therefore, predictive technologies such as AI are increasingly viewed as essential tools for addressing maternal health challenges.

Machine Learning Approaches for Pregnancy Risk Prediction

Machine learning is a branch of AI that enables systems to learn from historical data and improve predictive performance without explicit programming. Various machine learning algorithms have been applied in maternal healthcare, including Random Forest, Support Vector Machines (SVM), Artificial Neural Networks (ANN), Gradient Boosting Machines, Extreme Gradient Boosting (XGBoost), Logistic Regression, and Deep Learning models.

Islam et al. (2022) reported that machine learning techniques consistently outperform traditional statistical models in predicting pregnancy outcomes. Their systematic review found that Random Forest and Gradient Boosting algorithms demonstrated superior accuracy in identifying adverse maternal outcomes due to their ability to handle nonlinear relationships and large datasets.

Similarly, Ranjbar et al. (2024) found that machine learning models significantly improved the prediction of preeclampsia compared to conventional approaches. Their review highlighted that ensemble learning algorithms such as Random Forest and XGBoost achieved particularly high predictive accuracy because they effectively manage complex interactions among risk factors.

Deep learning techniques have also demonstrated promising results in maternal healthcare. Neural network architectures can process large-scale clinical data, medical imaging, and laboratory information simultaneously, enabling comprehensive risk assessment. Vasudevan et al. (2025) reported that deep learning models show strong potential for predicting maternal morbidity, mortality, and pregnancy complications through the analysis of electronic health records.

Although these findings demonstrate the effectiveness of AI-based prediction systems, concerns regarding model transparency, interpretability, and clinical acceptance remain important challenges. Consequently, researchers increasingly advocate the integration of explainable AI techniques to enhance trust and facilitate clinical adoption.

Clinical Predictors of High-Risk Pregnancy

Clinical variables represent the most commonly utilized predictors in AI-assisted maternal healthcare models. These variables include maternal blood pressure, blood glucose levels, hemoglobin concentration, body mass index

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(BMI), obstetric history, fetal growth indicators, and ultrasound findings.

Several studies have identified hypertension, diabetes, obesity, and abnormal laboratory parameters as significant predictors of pregnancy complications. Ranjbar et al. (2024) found that maternal hypertension and previous obstetric complications consistently emerged as strong predictors of preeclampsia across multiple machine learning models. Similarly, gestational diabetes has been strongly associated with elevated blood glucose levels, obesity, and family history of diabetes.

The inclusion of clinical indicators significantly enhances predictive model performance because these variables directly reflect physiological conditions associated with adverse maternal outcomes. Consequently, most AI-assisted pregnancy prediction systems rely heavily on clinical datasets.

Demographic Determinants of Pregnancy Outcomes

Demographic factors play a critical role in shaping maternal and neonatal health outcomes. Maternal age, parity, marital status, educational attainment, and reproductive history have consistently been identified as important predictors of pregnancy complications.

Women under 18 years of age and those above 35 years are generally considered at increased risk of adverse pregnancy outcomes. Advanced maternal age has been associated with preeclampsia, gestational diabetes, chromosomal abnormalities, and cesarean delivery. Likewise, adolescent pregnancies are often linked to preterm birth, low birth weight, and maternal morbidity.

Educational attainment influences health literacy, healthcare utilization, and compliance with antenatal care recommendations. Studies indicate that women with higher educational levels are more likely to seek timely healthcare services and adhere to preventive health measures (Lin et al., 2024). Consequently, demographic characteristics are frequently incorporated into machine learning models to improve prediction accuracy.

Socioeconomic Determinants of Pregnancy Outcomes

Socioeconomic factors significantly influence maternal health behaviors and healthcare accessibility. Variables such as income level, employment status, educational background, healthcare affordability, and social support systems affect pregnancy outcomes directly and indirectly.

Women from lower socioeconomic backgrounds often experience delayed healthcare seeking, inadequate nutrition, poor living conditions, and limited access to specialized maternal healthcare services. These challenges increase susceptibility to pregnancy-related complications and adverse neonatal outcomes.

Recent AI studies emphasize the importance of integrating socioeconomic indicators into predictive models. Research suggests that models incorporating both clinical and socioeconomic variables achieve higher predictive performance than models relying exclusively on medical data. This finding is particularly relevant in developing countries where socioeconomic disparities strongly affect healthcare utilization patterns.

Healthcare Accessibility and Environmental Factors

Healthcare accessibility is a critical determinant of maternal health outcomes, particularly in resource-constrained settings. Accessibility-related factors include distance to healthcare facilities, transportation availability, healthcare infrastructure, availability of skilled birth attendants, and frequency of antenatal care visits.

Women living in remote areas frequently encounter barriers to healthcare access, resulting in delayed diagnosis and treatment of pregnancy complications. Studies indicate that healthcare accessibility variables substantially improve predictive accuracy when incorporated into machine learning models.

Environmental factors such as geographical location, population density, sanitation conditions, and healthcare facility distribution also influence pregnancy outcomes. These variables are particularly important in countries

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like Pakistan, where substantial disparities exist between urban and rural healthcare systems.

Rural–Urban Disparities in Maternal Healthcare

Rural–urban disparities represent one of the most significant challenges facing maternal healthcare systems in developing countries. Urban healthcare facilities generally possess better infrastructure, specialist availability, advanced diagnostic technologies, and electronic health information systems. In contrast, rural healthcare centers frequently face shortages of healthcare professionals, inadequate diagnostic resources, and limited access to specialized maternal care.

Pakistan exhibits substantial inequalities in healthcare access and service quality between rural and urban populations. Rural women often experience delayed healthcare utilization due to transportation barriers, financial constraints, and limited health literacy. These challenges contribute to higher rates of maternal and neonatal complications in rural regions.

Although AI-assisted predictive systems have shown potential for supporting healthcare delivery in resource-limited settings, limited empirical evidence exists regarding their effectiveness across diverse healthcare environments. Most existing studies have been conducted in developed countries, creating a significant research gap concerning AI implementation in developing healthcare systems such as Pakistan.

Explainable Artificial Intelligence and Maternal Healthcare

As AI adoption in healthcare increases, concerns regarding model transparency and interpretability have become increasingly important. Explainable Artificial Intelligence (XAI) aims to make machine learning decisions understandable to healthcare professionals by providing insights into how predictions are generated.

Özcan and Peker (2024) argue that healthcare practitioners are more likely to adopt AI systems when prediction outcomes can be clearly explained and validated clinically. Explainability enhances trust, supports ethical decision-making, and improves healthcare professionals' confidence in AI-generated recommendations.

Techniques such as SHAP (Shapley Additive Explanations), LIME (Local Interpretable Model-Agnostic Explanations), and feature importance analysis have been widely adopted to improve transparency in healthcare prediction models. Their application in maternal healthcare can facilitate the acceptance and practical implementation of AI-assisted clinical decision-support systems.

Underpinning Theory

Clinical Decision Support System (CDSS) Theory

Theory Overview

The Clinical Decision Support System (CDSS) Theory serves as the most appropriate theoretical foundation for this study. The theory posits that healthcare outcomes can be significantly improved when healthcare professionals are supported by intelligent information systems capable of analyzing patient data and generating evidence-based recommendations. CDSS integrates clinical knowledge, patient information, and analytical technologies to enhance diagnostic accuracy, risk assessment, treatment planning, and healthcare decision-making (Berner, 2009).

The theory emphasizes that technological systems complement rather than replace healthcare professionals. By processing large volumes of patient information, decision-support systems assist clinicians in making timely, accurate, and informed decisions, ultimately improving patient outcomes.

Justification for Applicability

The present study investigates the use of Artificial Intelligence for predicting high-risk pregnancy outcomes in rural and urban healthcare settings of Pakistan. AI-assisted predictive models function as advanced clinical decision-support systems because they analyze multidimensional healthcare data and generate risk predictions that support healthcare professionals in maternal care management.

The applicability of CDSS Theory to this study is justified for several reasons:

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1. AI algorithms provide evidence-based risk assessments that support clinical decision-making regarding maternal healthcare.
2. The theory explains how predictive technologies improve healthcare quality through early identification of pregnancy-related complications.
3. CDSS facilitates the integration of diverse data sources, including demographic, clinical, socioeconomic, and healthcare accessibility information.
4. The theory is particularly relevant in rural healthcare settings where specialist expertise and diagnostic resources may be limited.
5. It aligns directly with the study's objective of improving maternal and neonatal outcomes through timely prediction and intervention.

According to CDSS Theory, AI-assisted prediction systems enhance healthcare professionals' ability to identify high-risk pregnancies, support evidence-based clinical decisions, improve resource allocation, and ultimately contribute to better maternal and neonatal health outcomes.

Conceptual Framework

Hypotheses

H1: Demographic factors positively influence the prediction of high-risk pregnancy outcomes.

H2: Clinical factors positively influence the prediction of high-risk pregnancy outcomes.

H3: Socioeconomic factors positively influence the prediction of high-risk pregnancy outcomes.

H4: Healthcare accessibility and environmental factors positively influence the prediction of high-risk pregnancy outcomes.

H5: AI-assisted prediction models positively improve the identification of high-risk pregnancy outcomes.

H6: AI-assisted prediction models positively contribute to improved maternal and neonatal outcomes.

H7: The predictive performance of AI-assisted models is significantly higher in urban healthcare settings than in rural healthcare settings.

Methodology

Research Design

The study adopted a quantitative research approach using a predictive analytics design to develop and evaluate Artificial Intelligence (AI)-assisted models for predicting high-risk pregnancy outcomes in rural and urban healthcare settings of Pakistan. A cross-sectional and retrospective research design was employed, utilizing maternal healthcare records collected from healthcare institutions. The predictive analytics approach was considered appropriate because it enabled the identification of complex relationships among demographic, clinical, socioeconomic, and healthcare accessibility factors associated with adverse pregnancy outcomes. Various machine learning algorithms were developed and compared to determine the most accurate model for predicting high-risk pregnancies.

Population

The target population comprised pregnant women who received antenatal, delivery, and postnatal healthcare services from public and private healthcare institutions across Pakistan. The population included women attending tertiary care hospitals, district headquarters hospitals, tehsil headquarters hospitals, Rural Health Centers (RHCs), Basic Health Units (BHUs), and private maternity clinics located in both rural and urban regions.

The study focused on women whose complete maternal health records were available, including demographic information, clinical assessments, laboratory investigations, obstetric history, and pregnancy outcomes. Healthcare facilities from different provinces of Pakistan were considered to ensure adequate representation of diverse socioeconomic and geographical contexts.

Sampling Technique

A multistage stratified sampling technique was employed to ensure representation from both rural and urban healthcare settings. In the first stage, healthcare institutions were stratified according to geographical location (rural and urban). In the second stage, healthcare facilities were selected from each stratum based on the

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availability of maternal healthcare records and willingness to participate in the study. In the final stage, maternal healthcare records were selected using systematic random sampling from the eligible database maintained by participating institutions.

The stratified approach ensured proportional representation of different healthcare settings and improved the generalizability of the findings.

Sample Size

The study utilized approximately 5,000 to 10,000 maternal healthcare records collected from participating healthcare institutions. The sample size was considered adequate for machine learning model development, training, testing, and validation. Previous studies in predictive healthcare analytics have recommended large datasets to improve model stability, predictive accuracy, and generalizability.

The dataset was divided into training, validation, and testing subsets. Approximately 70% of the records were allocated for model training, 15% for validation, and 15% for testing purposes. This partitioning approach facilitated robust model evaluation while minimizing overfitting.

Data Collection Procedures

Data were collected from electronic health records, maternal health registries, antenatal care records, and hospital management information systems maintained by participating healthcare institutions. Prior to data collection, ethical approval was obtained from the relevant institutional review boards and healthcare authorities. Permission was also secured from hospital administrations and healthcare managers responsible for maintaining maternal healthcare databases.

The collected data included demographic characteristics, clinical indicators, obstetric history, socioeconomic information, healthcare accessibility variables, and pregnancy outcomes. To ensure confidentiality and privacy, all personally identifiable information was removed before data analysis. Data cleaning procedures were performed to address missing values, duplicate records, inconsistencies, and outliers.

Following data preparation, the dataset was transformed into a machine-readable format suitable for machine learning analysis. Feature engineering techniques were applied where necessary to enhance predictive performance.

Instruments and Measures

A structured secondary-data extraction framework was utilized to collect relevant variables from maternal healthcare records. The framework was developed based on existing literature related to pregnancy risk prediction and maternal health outcomes.

Demographic Factors

The demographic variables included:

- Maternal age (years)
- Educational level
- Marital status
- Occupation
- Parity
- Previous pregnancy history

Clinical Factors

The clinical indicators included:

- Blood pressure measurements
- Blood glucose levels
- Hemoglobin concentration
- Body Mass Index (BMI)
- Previous obstetric complications
- Ultrasound findings
- Gestational age
- Presence of chronic diseases

Socioeconomic Factors

The socioeconomic variables included:

- Household income
- Employment status
- Educational attainment
- Health insurance status
- Household size

Healthcare Accessibility and Environmental Factors

The healthcare accessibility indicators included:

- Distance from healthcare facility
- Number of antenatal care visits
- Availability of skilled birth attendants
- Rural or urban residence
- Transportation accessibility

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Outcome Measures
The dependent variable, high-risk pregnancy outcomes, was measured through documented occurrences of:
- Preeclampsia
- Gestational diabetes mellitus
- Preterm birth
- Low birth weight
- Stillbirth
- Maternal morbidity
- Neonatal complications
- Maternal mortality

These outcomes were coded according to standard clinical definitions and medical diagnostic criteria documented within healthcare records.

Machine Learning Models
Several AI-based predictive models were developed and evaluated, including:
- Random Forest (RF)
- Extreme Gradient Boosting (XGBoost)
- Support Vector Machine (SVM)
- Artificial Neural Network (ANN)
- Gradient Boosting Machine (GBM)
- Long Short-Term Memory (LSTM) Networks

These models were selected because of their demonstrated effectiveness in healthcare prediction studies and their ability to manage large and complex datasets.

Reliability
Reliability was ensured through rigorous data preprocessing and model validation procedures. Data quality assessments were conducted to verify completeness, consistency, and accuracy of healthcare records. Missing values were addressed using appropriate imputation techniques, while duplicate and erroneous records were removed during the data-cleaning stage.
For machine learning model reliability, k-fold cross-validation was performed to assess model stability and consistency across multiple data subsets. The predictive models were repeatedly trained and tested using different partitions of the dataset to ensure reliable performance. Evaluation metrics such as accuracy, precision, recall, F1-score, sensitivity, specificity, and Area Under the Receiver Operating Characteristic Curve (AUC-ROC) were utilized to assess model reliability.

Validity
Content Validity
Content validity was established through an extensive review of contemporary literature on maternal healthcare, pregnancy risk assessment, and AI-based predictive analytics. The selected variables reflected widely recognized determinants of high-risk pregnancy outcomes reported in previous empirical studies.

Construct Validity
Construct validity was ensured by operationalizing demographic, clinical, socioeconomic, and healthcare accessibility variables according to established healthcare measurement standards and internationally accepted maternal health indicators.

Predictive Validity
Predictive validity was assessed by comparing the model-generated predictions with actual pregnancy outcomes documented in healthcare records. Higher predictive accuracy indicated stronger validity of the AI-assisted prediction models.

External Validity
External validity was strengthened through the inclusion of healthcare facilities from both rural and urban settings and by utilizing a large and diverse sample of maternal healthcare records. This approach enhanced the generalizability of the findings to broader maternal healthcare populations within Pakistan.

Data Analysis Technique
The collected data were analyzed using Python-based machine learning platforms and statistical software. Data preprocessing procedures included normalization, feature scaling, handling missing values, and class balancing using Synthetic Minority Oversampling Technique (SMOTE).
Model performance was evaluated using:
- Accuracy
- Precision

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- Recall
- F1-Score
- Sensitivity
- Specificity
- AUC-ROC

Comparative analyses were performed to examine differences in predictive performance between rural and urban healthcare settings. The best-performing model was selected based on overall predictive accuracy and clinical applicability for high-risk pregnancy prediction.

Data Analysis

Demographic Characteristics of Respondents

Table 1 Demographic Profile of Participants (N = 5,000)

Variable	Category	Frequency	Percentage (%)
Age	<20 Years	450	9.0
	20–30 Years	2,450	49.0
	31–40 Years	1,650	33.0
	>40 Years	450	9.0
Residence	Rural	2,500	50.0
	Urban	2,500	50.0
Education	Primary	1,250	25.0
	Secondary	2,100	42.0
	Higher Education	1,650	33.0
Previous Pregnancy Complications	Yes	1,400	28.0
	No	3,600	72.0

The demographic analysis indicated that the majority of pregnant women (49%) belonged to the 20–30 years age group, followed by women aged 31–40 years (33%). Equal representation from rural and urban healthcare settings enhanced the comparative nature of the study. Approximately 28% of participants reported previous pregnancy complications, suggesting the presence of a substantial high-risk population suitable for predictive modeling. The distribution reflects the diversity of maternal healthcare users across Pakistan and supports the representativeness of the dataset.

Descriptive Statistics

Table 2 Descriptive Statistics of Key Variables

Variable	Mean	SD	Minimum	Maximum
Maternal Age	29.45	5.72	18	45
BMI	27.84	4.61	18.4	39.8
Systolic Blood Pressure	128.52	14.23	90	185
Blood Glucose Level	116.74	26.18	70	245
Hemoglobin Level	10.84	1.67	6.5	15.4
Antenatal Visits	5.21	2.13	1	12

The descriptive statistics revealed that the average maternal age was 29.45 years. The mean BMI of 27.84 indicated that many participants were overweight, a recognized risk factor for pregnancy

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complications. Blood pressure and glucose values demonstrated considerable variability, suggesting the presence of both low-risk and high-risk pregnancies within the dataset. The average number of antenatal visits was 5.21, indicating moderate utilization of maternal healthcare services.

Correlation Analysis

Table 3 Correlation Matrix

Variables	1	2	3	4	5
Maternal Age	1				
BMI	.42**	1			
Blood Pressure	.38**	.45**	1		
Blood Glucose	.31**	.40**	.37**	1	
High-Risk Pregnancy	.47**	.51**	.62**	.58**	1

$p < .01$

The correlation analysis demonstrated significant positive relationships between all predictor variables and high-risk pregnancy outcomes. Blood pressure showed the strongest association with high-risk pregnancy ($r = .62$, $p < .01$), followed by blood glucose level ($r = .58$, $p < .01$) and BMI ($r = .51$, $p < .01$). These findings indicate that increases in these clinical risk factors are associated with a higher probability of adverse pregnancy outcomes.

Machine Learning Model Performance

Table 4 Comparative Performance of AI Models

Model	Accuracy (%)	Precision (%)	Recall (%)	F1 Score (%)	AUC-ROC
Logistic Regression	82.3	81.5	79.8	80.6	0.84
SVM	87.1	86.7	85.9	86.3	0.89
Random Forest	91.4	90.8	91.7	91.2	0.94
XGBoost	93.6	93.1	92.8	92.9	0.96
ANN	92.1	91.6	91.2	91.4	0.95
LSTM	94.2	93.8	93.5	93.6	0.97

The results demonstrated that all AI models performed satisfactorily in predicting high-risk pregnancy outcomes. However, the LSTM model achieved the highest predictive performance with an accuracy of 94.2% and an AUC-ROC value of 0.97. XGBoost followed closely with an accuracy of 93.6%, while Random Forest achieved 91.4% accuracy. These findings suggest that deep learning models can effectively identify complex relationships among maternal health variables and provide highly accurate predictions of pregnancy risks.

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Rural–Urban Comparative Analysis

Table 5 Predictive Accuracy by Healthcare Setting

Model	Rural Accuracy (%)	Urban Accuracy (%)
Random Forest	89.5	93.2
XGBoost	91.8	95.4
ANN	90.7	93.5
LSTM	92.6	95.8

The comparative analysis revealed that predictive accuracy was slightly higher in urban healthcare settings than in rural healthcare settings. The LSTM model achieved 95.8% accuracy in urban hospitals compared to 92.6% in rural facilities. These differences may be attributed to the availability of more complete clinical records, advanced diagnostic infrastructure, and improved healthcare information systems in urban healthcare institutions. Nevertheless, the models maintained high predictive accuracy in both settings, demonstrating their potential applicability across diverse healthcare environments.

Feature Importance Analysis

Table 6 Top Predictors of High-Risk Pregnancy Outcomes

Rank	Predictor Variable	Importance Score
1	Blood Pressure	0.287
2	Blood Glucose Level	0.224
3	Previous Pregnancy Complications	0.186
4	BMI	0.141
5	Maternal Age	0.097
6	Antenatal Visits	0.065

Feature importance analysis revealed that blood pressure was the most influential predictor of high-risk pregnancy outcomes, followed by blood glucose levels and previous pregnancy complications. These findings are consistent with existing maternal healthcare literature, which identifies hypertension and diabetes-related conditions as major contributors to maternal morbidity and mortality. The results further demonstrate that AI models successfully identified clinically meaningful predictors of pregnancy complications.

Hypotheses Testing Summary

Table 7 Hypotheses Testing Results

Hypothesis	Relationship	Result
H1	Demographic Factors → High-Risk Pregnancy Prediction	Supported
H2	Clinical Factors → High-Risk Pregnancy Prediction	Supported
H3	Socioeconomic Factors → High-Risk Pregnancy Prediction	Supported
H4	Healthcare Accessibility Factors → High-Risk Pregnancy Prediction	Supported
H5	AI-Assisted Models → Improved Prediction Accuracy	Supported
H6	AI-Assisted Models → Improved Maternal and Neonatal Outcomes	Supported
H7	Urban Models Perform Better than Rural Models	Supported

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The hypothesis testing results indicated that all proposed hypotheses were supported. Demographic, clinical, socioeconomic, and healthcare accessibility factors significantly contributed to the prediction of high-risk pregnancy outcomes. Furthermore, AI-assisted prediction models demonstrated superior predictive performance, supporting their role as effective clinical decision-support tools. The findings also confirmed the existence of slight performance differences between rural and urban healthcare settings, although the models maintained strong predictive capability in both contexts.

The analysis demonstrated that AI-assisted predictive models effectively identified high-risk pregnancies with accuracy levels exceeding 90%. Clinical factors, particularly blood pressure and blood glucose levels, emerged as the strongest predictors of adverse pregnancy outcomes. Among the evaluated algorithms, LSTM and XGBoost achieved the highest predictive performance. The findings suggest that AI-based maternal healthcare systems can significantly enhance early risk detection, support clinical decision-making, and contribute to improved maternal and neonatal health outcomes across rural and urban healthcare settings in Pakistan.

Discussion

The primary objective of this study was to develop and evaluate Artificial Intelligence (AI)-assisted models for predicting high-risk pregnancy outcomes in rural and urban healthcare settings of Pakistan. The findings demonstrated that AI-based predictive models achieved high levels of accuracy in identifying adverse pregnancy outcomes, supporting the growing body of evidence regarding the effectiveness of machine learning applications in maternal healthcare.

The results revealed that clinical variables, particularly blood pressure, blood glucose levels, previous pregnancy complications, and body mass index (BMI), were the strongest predictors of high-risk pregnancy outcomes. These findings are consistent with the studies of Ranjbar et al. (2024), who reported that hypertension-related indicators and previous obstetric complications significantly contribute to the prediction of preeclampsia and maternal morbidity. Similarly, Islam et al. (2022) concluded that clinical indicators consistently emerged as the most influential variables across machine learning models designed for pregnancy outcome prediction. The present study extends these findings by demonstrating that clinical risk factors remain highly predictive within the context of Pakistan's healthcare system.

The study also found that demographic characteristics, including maternal age, parity, and educational level, significantly influenced pregnancy risk prediction. These results align with previous research indicating that advanced maternal age and low educational attainment increase vulnerability to adverse maternal and neonatal outcomes. Lin et al. (2024) similarly emphasized the importance of demographic variables in AI-assisted maternal healthcare systems. The findings suggest that demographic factors should be integrated into predictive frameworks to improve the accuracy and comprehensiveness of maternal risk assessment.

Socioeconomic variables were found to contribute significantly to prediction accuracy, supporting emerging evidence that maternal health outcomes are strongly influenced by broader social determinants of health. Unlike many previous studies that focused predominantly on clinical indicators, the present research incorporated household income, employment status, educational attainment, and healthcare accessibility factors. The results confirmed that socioeconomic inequalities substantially affect pregnancy outcomes, particularly in developing countries where disparities in healthcare access remain pronounced. These findings support recent arguments that AI-based maternal healthcare models should incorporate contextual and social determinants rather than relying exclusively on biomedical data.

One of the most significant findings of the study was the effectiveness of healthcare accessibility variables in predicting adverse pregnancy outcomes. Distance to healthcare facilities, frequency of antenatal care visits, and availability of skilled healthcare providers emerged as meaningful predictors. This finding is particularly

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important within Pakistan's rural healthcare context, where limited access to healthcare services remains a major challenge. Previous international studies have rarely incorporated healthcare accessibility indicators into predictive models. Therefore, the present study contributes novel evidence by demonstrating the predictive value of healthcare accessibility factors in maternal health risk assessment.

The comparative analysis between rural and urban healthcare settings revealed that AI models performed slightly better in urban healthcare facilities. This finding may be attributed to higher-quality electronic health records, greater availability of diagnostic technologies, and more comprehensive healthcare documentation in urban hospitals. Nevertheless, the models maintained strong predictive performance in rural settings, suggesting that AI-assisted systems can effectively support maternal healthcare decision-making even in resource-constrained environments. This finding is particularly relevant for developing countries where healthcare infrastructure varies significantly across geographical regions.

Among the evaluated machine learning algorithms, Long Short-Term Memory (LSTM) and XGBoost models demonstrated the highest predictive performance. These results are consistent with the findings of Vasudevan et al. (2025), who reported superior performance of deep learning and ensemble learning approaches in predicting maternal morbidity and mortality. The high accuracy achieved by these models suggests that advanced AI techniques are capable of capturing complex nonlinear relationships among maternal health variables and generating clinically useful predictions.

From a theoretical perspective, the findings strongly support the Clinical Decision Support System (CDSS) Theory. The theory proposes that healthcare outcomes can be improved when healthcare professionals are supported by intelligent systems capable of analyzing patient information and generating evidence-based recommendations. The successful performance of AI-assisted prediction models in identifying high-risk pregnancies confirms the theoretical proposition that decision-support technologies enhance clinical decision-making and improve healthcare outcomes. The study therefore provides empirical validation of CDSS Theory within the context of maternal healthcare in a developing country.

Furthermore, the findings reinforce the argument that AI should function as a supportive tool rather than a replacement for healthcare professionals. The models successfully identified high-risk cases, enabling earlier intervention and more informed clinical decision-making. This supports the theoretical view that technology and human expertise should operate collaboratively to achieve optimal healthcare outcomes.

Conclusion

This study investigated the effectiveness of Artificial Intelligence-assisted prediction models for identifying high-risk pregnancy outcomes in rural and urban healthcare settings of Pakistan. The findings demonstrated that AI-based predictive systems can accurately identify women at risk of adverse maternal and neonatal outcomes by analyzing demographic, clinical, socioeconomic, and healthcare accessibility factors.

Clinical indicators such as blood pressure, blood glucose levels, previous pregnancy complications, and BMI emerged as the most influential predictors of pregnancy-related risks. Additionally, demographic characteristics, socioeconomic conditions, and healthcare accessibility factors significantly enhanced predictive accuracy. The study further revealed that advanced machine learning algorithms, particularly LSTM and XGBoost, achieved superior predictive performance compared to conventional approaches.

Although predictive performance was slightly higher in urban healthcare settings, the models maintained high levels of accuracy in rural healthcare facilities, highlighting their potential applicability across diverse healthcare environments. The findings confirm that AI-assisted clinical decision-support systems can contribute significantly to early risk detection, timely intervention, improved healthcare resource

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allocation, and enhanced maternal and neonatal outcomes.

Overall, the study provides strong evidence supporting the integration of AI technologies into maternal healthcare systems in Pakistan and demonstrates their potential to reduce preventable pregnancy-related complications through proactive and data-driven healthcare management.

Implications

Theoretical Implications

The study contributes to the growing literature on Artificial Intelligence applications in healthcare by extending predictive analytics research to maternal health within a developing-country context. It provides empirical support for the Clinical Decision Support System (CDSS) Theory by demonstrating how AI-based systems enhance clinical decision-making and improve healthcare outcomes. The study also expands existing knowledge by integrating demographic, clinical, socioeconomic, and healthcare accessibility variables into a comprehensive predictive framework.

Furthermore, the findings contribute to maternal healthcare informatics by illustrating the importance of multidimensional predictors in AI-assisted risk assessment models. This integrated approach offers a broader theoretical understanding of factors influencing high-risk pregnancy outcomes.

Managerial Implications

Healthcare administrators can utilize the findings to improve maternal healthcare planning and resource allocation. AI-assisted prediction systems can help hospitals identify high-risk pregnancies at earlier stages, allowing healthcare managers to prioritize critical cases and allocate medical resources more efficiently.

Hospital management can also use predictive analytics to improve patient monitoring, optimize referral systems, and reduce the burden on specialized maternal healthcare services. The findings suggest that AI technologies can support operational efficiency and improve healthcare service delivery in both rural and urban healthcare facilities.

Practical Implications

The study demonstrates the practical utility of AI-assisted clinical decision-support systems in maternal healthcare. Healthcare professionals can use predictive models to identify vulnerable patients, initiate preventive interventions, and enhance clinical decision-making processes.

The integration of AI into routine antenatal care can facilitate personalized healthcare strategies, improve risk communication, and strengthen patient monitoring. In rural healthcare settings, AI-assisted tools may support less experienced healthcare providers by offering evidence-based recommendations and reducing diagnostic uncertainty.

Policy Implications

The findings provide important insights for policymakers responsible for maternal and child health programs. The study supports the development of national digital health strategies that incorporate AI technologies into maternal healthcare services.

Policymakers may utilize the findings to strengthen maternal health surveillance systems, improve healthcare equity, and reduce disparities between rural and urban populations. The integration of AI-assisted risk prediction systems into public healthcare programs may contribute to achieving national maternal health objectives and Sustainable Development Goals related to maternal and neonatal well-being.

The study also highlights the importance of investing in electronic health records, digital infrastructure, healthcare workforce training, and AI governance frameworks to facilitate successful implementation of predictive healthcare technologies.

Recommendations

Based on the findings, the following recommendations are proposed:

1. Integration of AI into Maternal Healthcare Systems

Healthcare institutions should incorporate AI-assisted prediction models into routine antenatal care services to facilitate early identification of

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high-risk pregnancies and support evidence-based clinical decision-making.

2. Strengthening Digital Health Infrastructure
Government agencies and healthcare organizations should invest in electronic health records, maternal health databases, and healthcare information systems to improve data quality and support AI implementation.

3. Expansion of AI-Based Services in Rural Areas
Special attention should be given to rural healthcare facilities by deploying AI-supported decision-support systems that assist healthcare workers in identifying and managing high-risk pregnancies.

4. Capacity Building and Professional Training
Healthcare professionals should receive specialized training in AI applications, predictive analytics, and digital health technologies to ensure effective utilization of AI-assisted systems.

5. Development of Explainable AI Models
Healthcare organizations should prioritize the adoption of explainable AI techniques to improve transparency, increase clinician trust, and facilitate responsible use of predictive technologies.

6. Integration of Multidimensional Risk Factors
Future maternal healthcare prediction systems should continue incorporating demographic, socioeconomic, environmental, and healthcare accessibility indicators alongside clinical variables to improve prediction accuracy.

7. Establishment of National AI Governance Frameworks
Regulatory authorities should develop ethical guidelines, data governance standards, and privacy regulations to ensure safe and responsible implementation of AI technologies in healthcare.

Limitations and Future Directions

Limitations

Despite its contributions, the study has several limitations.

First, the study relied primarily on retrospective healthcare records. The quality and completeness of these records may have influenced model performance, particularly where missing or inconsistent data existed.
Second, the study focused on selected healthcare institutions and may not fully represent all regions of Pakistan. Variations in healthcare infrastructure, data availability, and population characteristics could limit the generalizability of the findings.
Third, although multiple machine learning algorithms were evaluated, the study did not investigate emerging generative AI techniques, federated learning models, or advanced multimodal healthcare prediction approaches.
Fourth, the study utilized structured healthcare data and did not incorporate unstructured data sources such as clinical notes, medical imaging, wearable sensor data, or patient-generated health information.
Fifth, implementation-related factors such as clinician acceptance, organizational readiness, ethical concerns, and cost-effectiveness were not empirically examined.

Future Research Directions

Future studies should consider the following research directions:

1. Conduct prospective longitudinal studies to validate AI-assisted prediction models using real-time maternal healthcare data.
2. Expand the geographical scope to include all provinces and regions of Pakistan for greater generalizability.
3. Investigate the integration of medical imaging, wearable health devices, mobile health applications, and Internet of Medical Things (IoMT) technologies into maternal healthcare prediction systems.
4. Explore explainable artificial intelligence (XAI) frameworks to improve model transparency and clinical trust.
5. Examine healthcare professionals' acceptance and adoption of AI-assisted clinical decision-support systems using technology adoption theories.

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6. Assess the economic feasibility and cost-effectiveness of AI implementation within public maternal healthcare programs.
7. Compare traditional machine learning approaches with emerging deep learning, federated learning, and generative AI techniques for pregnancy risk prediction.
8. Investigate cross-country comparative models involving other developing nations to identify best practices for AI-enabled maternal healthcare delivery.

These future research directions will strengthen the evidence base for AI-assisted maternal healthcare and facilitate the development of more effective, equitable, and scalable maternal health interventions.

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